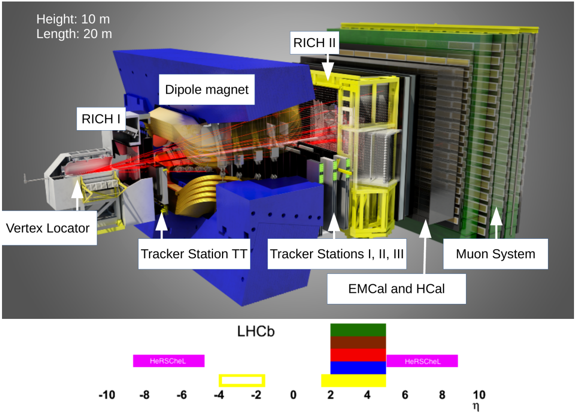
# Fixed-target & heavy-ion collision results from LHCb

Michael Winn on behalf of the LHCb collaboration

Laboratoire de l'Accélérateur Linéaire, Orsay

LHC seminar, CERN, 21.08.2018

# The LHCb detector

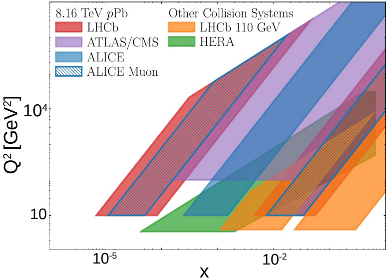


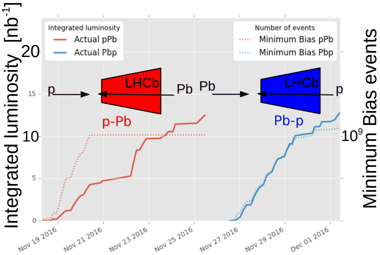

JINST 3 (2008) S08005.

- precise tests of the Standard Model in the flavour sector
- spectacular QCD spectroscopy and precision EW measurements
- flexible trigger down to low-$p_T$ with high rates in fixed-target geometry
- High-Energy Physics eagerly waiting for news from lepton universality

… LHCb is even more than this!

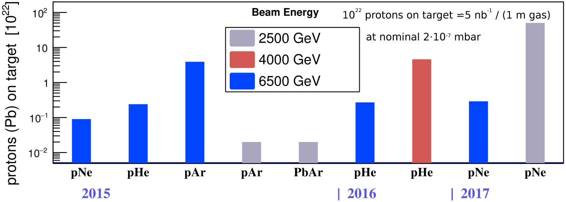
# Unique forward kinematics in heavy-ion collider mode

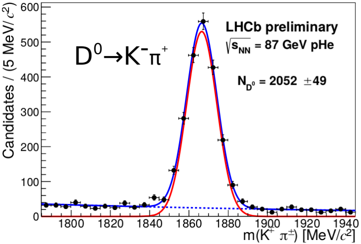


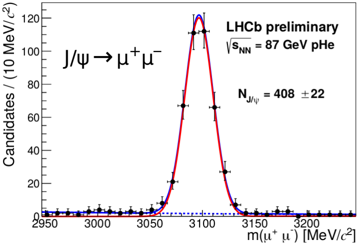




- 2016 $p$Pb run at $\sqrt{s_{NN}} = 8.16$ TeV:
  - $10^9$ minimum bias collisions in $p$Pb and Pb$p$ mode
  - $34\,\text{nb}^{-1}$ in $p$Pb+Pb$p$ for heavy-flavour/other probes processed in HLT: $\approx$ 0.5 million J/$\psi$ in $p$Pb, Pb$p$ each
- Ion-ion: 10 $\mu b^{-1}$ PbPb and 0.4 $\mu b^{-1}$ XeXe
  $\rightarrow$ 2018 PbPb aiming for a factor 10 more
- heavy-ion and low-$x$ with inclusive and exclusive production channels

# Unique fixed target mode at the LHC




- **S**ystem for **m**easuring **O**verlap with **G**as: most precise LHC luminosity
  LHCb-PAPER-2014-047, JINST 9 (2014) no.12
- used as internal gas target for physics parasitic to collider data taking
- cosmic ray and heavy-ion related physics with He, Ne and Ar targets

# Today's selection

- $\bar{p}$-production in $p$He fixed-target collisions:
  **reference for direct cosmic rays**

  Final results at $\sqrt{s_{NN}} = 110$ GeV LHCb-PAPER-2018-031, arXiv:1808.06127

- charm production in fixed-target collisions in $p\ ^{4}\mathrm{He}/^{40}\mathrm{Ar}$:
  **intermediate/large-$x$ & reference for ion-ion collisions**

  $D^0$ and J/$\psi$ production LHCb-PAPER-2018-023, in preparation

- heavy-flavour and quarkonium production in $p$Pb:
  **low-$x$, energy loss tests & reference for ion-ion collisions**
  New $\Lambda_c^+$ at $\sqrt{s_{NN}} = 5$ TeV & $\Upsilon$(nS) at $\sqrt{s_{NN}} = 8.16$ TeV
  LHCb-PAPER-2018-021, in preparation. & LHCb-PAPER-2018-035, in preparation.
  J/$\psi$ at $\sqrt{s_{NN}} = 8.16$ TeV LHCb-PAPER-2017-014, PLB 774 (2017) 159

  D$^0$ at $\sqrt{s_{NN}} = 5$ TeV LHCb-PAPER-2017-015, JHEP 10 (2017) 090

- exclusive photonuclear J/$\psi$ production in ultra-peripheral PbPb collisions:
  **probe low-$x$ and nuclear shadowing**

  LHCb-CONF-2018-003

# $\bar{p}$ from space: indirect search for the unknown

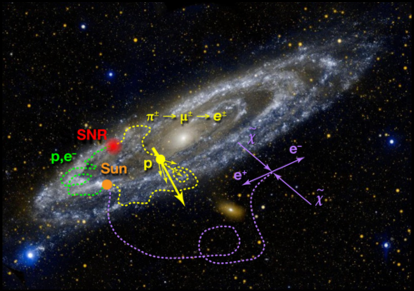
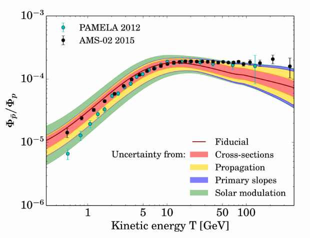


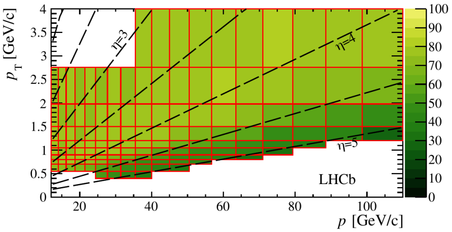

Image: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker.

- matter:
  primary cosmic rays from Supernovae Remnants (SNR) and other sources
- possible exotic **antimatter** sources in space: dark matter annihilations
- irreducible **background**: primary cosmic rays hitting interstellar medium, **Hydrogen and Helium**, producing secondary cosmic rays containing $\bar{p}$
- direct charged cosmic ray detection in space:
  **precision** data with Pamela and AMS

# Production cross sections in $p$He: a crucial missing piece



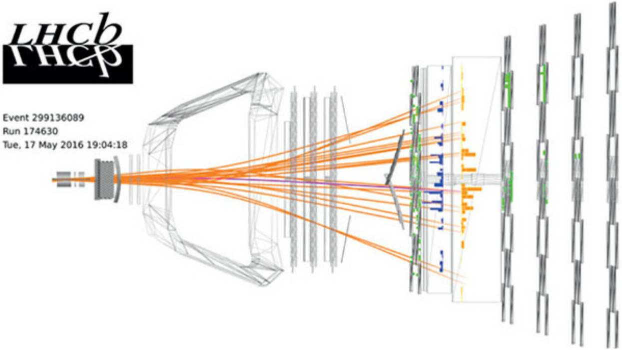

comparsion with AMS data JCAP 1509 (2015) no.09, 023




$\bar{p}$-measurement kinematics, $z$-axis $\epsilon_{rec}$.

- flux prediction uncertainties in 10-100 GeV kinetic energy range: dominated by production cross sections uncertainties
- $\bar{p}$-production in $p$He collisions never directly measured
- LHCb in fixed-target mode: pioneer with well suited kinematics
- publication submitted to PRL, LHCb-PAPER-2018-031, arXiv:1808.06127

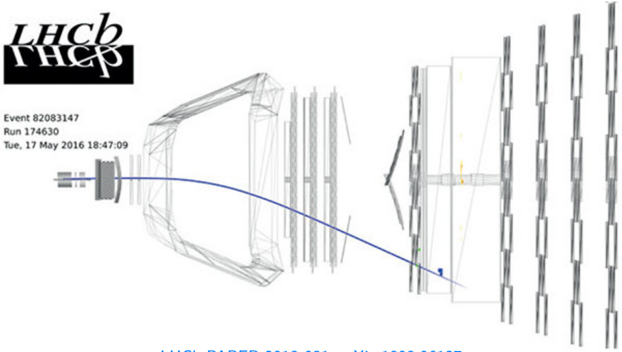
# Prompt $\bar{p}$-production in $p$He collisions at $\sqrt{s_{NN}} = 110$ GeV




LHCb-PAPER-2018-031, arXiv:1808.06127

- proton beam 1 hits He-gas pressure $O(10^{-7})$ mbar
- $\bar{p}$ momentum: 12-110 GeV/$c$ $\bar{p}$ transverse momentum: 0.4-4 GeV/$c$
  lower bound: RICH $K^-$-threshold
- prompt: excluding weak hyperon decays
- trigger: activity in scintillator $+ \geqslant 1$ track at software stage
- event vertex: $-700 < z < 100$ mm
- simulation: minimum bias EPOS LHC PRC 92, 034906 (2015)

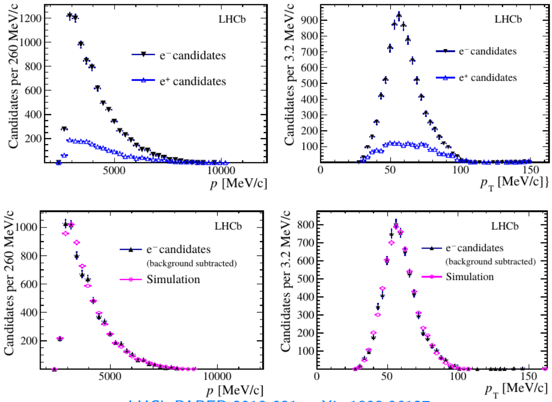
# $\bar{p}$-production in $p$He collisions: luminosity determination




LHCb-PAPER-2018-031, arXiv:1808.06127

- gas pressure not precisely known
  $\rightarrow$ indirect luminosity measurement
- elastic scattering of proton beam with atomic $e^-$ of He-gas:
  $\rightarrow$ QED and proton form factors
- simulation: ESEPP for $e^-$ scattering J. Phys. G41 (2014) 115001

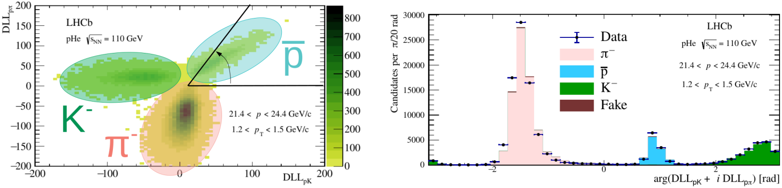
# $\bar{p}$-production in $p$He collisions: luminosity determination




LHCb-PAPER-2018-031, arXiv:1808.06127

- single soft $e^-$ in $11 < \Theta < 21$ mrad: $< \epsilon_{rec} >= 16.3\%$
- loose $e^-/e^+$-ID via energy in ECal
- background charge symmetric: $e^+$ as background proxy from data
- BDT-based selection on geometry, kinematics + exclusivity: $\epsilon = 96$ %
- main uncertainty low $< \epsilon_{rec} >$: 5 % relative uncertainty

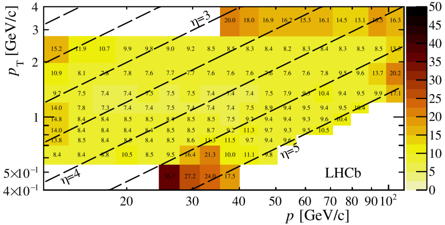
# $\bar{p}$-production in $p$He collisions: particle identification




LHCb-PAPER-2018-031, arXiv:1808.06127

- negatively charged tracks: $\pi^-$, K$^-$ and $\bar{p}$; 1.7 % fakes (simulation)
- PID with 2 RICH detectors
- 3 set of templates:
  - $p$He simulation (default)
  - $p$He data: tracks from weakly decaying light-flavour and $\phi \rightarrow KK$
  - $pp$ data: as in $p$He and $D$-meson decays
- 2 methods:
  - 2-dimensional binned extended-max. likelihood fit
  - cut & count

# Prompt $\bar{p}$-production in $p$He collisions: uncertainties

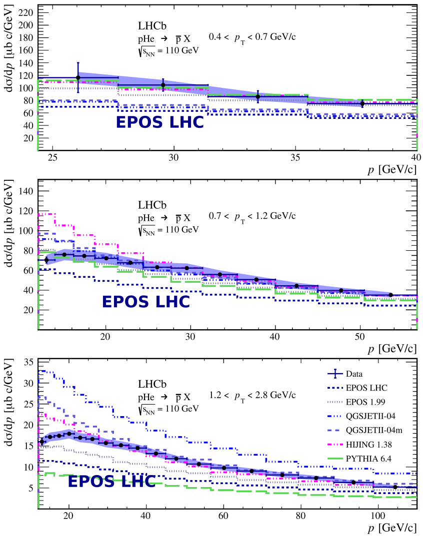



| | |
|---|---|
| Statistical | |
| $\bar{p}$ yields | 0.5 – 11% (< 2% for most bins) |
| Luminosity | 1.5 – 2.3% |
| Correlated systematic | |
| Luminosity | 6.0% |
| Event and PV selection | 0.3% |
| PV reconstruction | 0.4 – 2.9% |
| Tracking | 1.3 – 4.1% |
| Non-prompt background | 0.3 – 0.5% |
| Target purity | 0.1% |
| PID | 3.0 – 6.0% |
| Uncorrelated systematic | |
| Tracking | 1.0% |
| IP cut efficiency | 1.0% |
| PV reconstruction | 1.6% |
| PID | 0 – 36% (< 5% for most bins) |
| Simulated sample size | 0.4 – 11% (< 2% for most bins) |

LHCb-PAPER-2018-031, arXiv:1808.06127

- luminosity and PID dominating uncertainties
- **uncertainties below 10%** for most kinematic bins

# Prompt $\bar{p}$-production cross section results in $p$He collisions




LHCb-PAPER-2018-031, arXiv:1808.06127

EPOS LHC, EPOS 1.99, QGSJET-II, QGSJETII-04m, Hijing, PYTHIA 6.4, ICRC '17: difference summary by T. Pierog

- uncertainties **smaller than model spread**

  differ by hadronisation & parton model+dynamics

- **EPOS LHC** tuned on LHC collider data **underestimates** $\bar{p}$-production

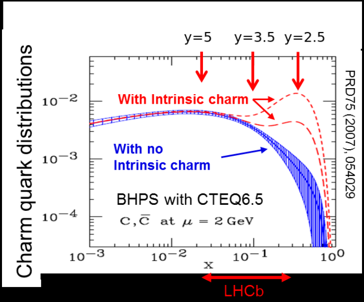
- $\sigma_{vis}^{LHCb}/\sigma_{vis}^{EPOS-LHC}$ $= 1.08 \pm 0.07(lumi) \pm 0.03(primary\ vertex)$

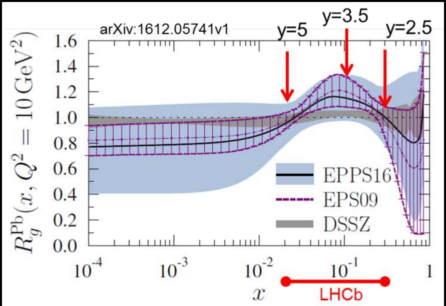
  $\rightarrow$ discrepancy: $\bar{p}$ yield/event

- **unique and precise**: decisive contribution to shrink background uncertainties in dark matter searches in space

- natural $p$He extensions:
  - inclusive $\bar{p}$ with hyperon decays
  - charged $\pi, K, p$ spectra
  - $\sqrt{s_{NN}} = 87$ GeV data

# Charm production in fixed-target *p*He and *p*Ar



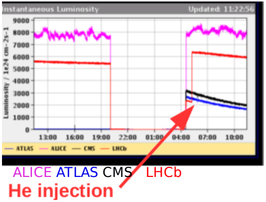



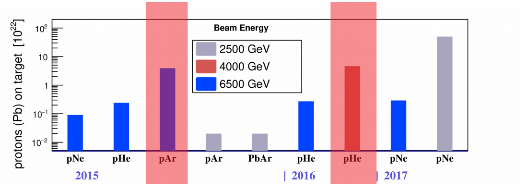

PRD 75 (2007) 054029

EPJC 77 (2017), 163.

- nuclear modification of parton distribution function
- 'valence-like' intrinsic charm via backward rapidity coverage
- reference for future Pb–A fixed target studies for Quark-Gluon Plasma:
  $\rightarrow$ quarkonium suppression patterns and open charm:
  intermediate $\sqrt{s}$ between SPS & top RHIC energy

# Charm production in fixed-target configuration: data sets

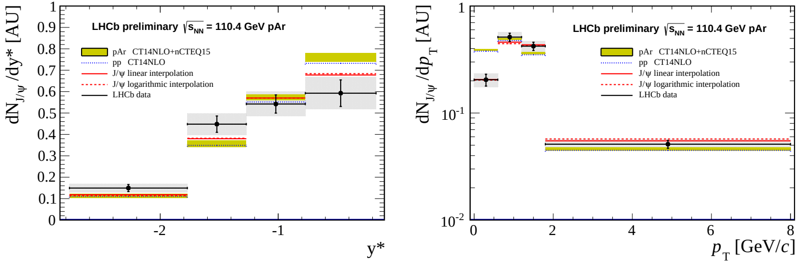



- bridging the gap:
  - Tevatron/HERA fixed-target up to $\sqrt{s_{NN}} = 42$ GeV
  - RHIC at $\sqrt{s_{NN}} = 200$ GeV
- *p*He at 87 GeV: luminosity as for 110 GeV $\bar{p}$-analysis
- indirect luminosity not available for 2015 *p*Ar

| System | $\sqrt{s_{NN}}$ | Protons on target | Target A | $L_{int}$ |
|---|---|---|---|---|
| *p*Ar | 110 GeV | $4 \cdot 10^{22}$ | 40 | - |
| *p*He | 87 GeV | $5 \cdot 10^{22}$ | 4 | $7.58 \pm 0.47$ nb$^{-1}$ |

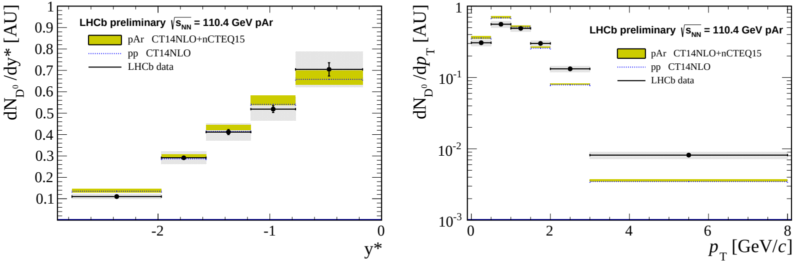
# $J/\psi$ production in $p$Ar collisions at $\sqrt{s_{NN}} = 110$ GeV




LHCb-PAPER-2018-022, in preparation.

- backward hemisphere in centre-of-mass probing Bjorken-$x$: 0.02-0.16
  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y*}$
- shape in agreement for rapidity with phenomenological parametrisation
  JHEP 1303 (2013) 122
- HELAC-onia model EPJC 77 (2017) designed and tuned for collider data
  reasonable for rapidity, not working very well for $p_T$

# $D^0$ production in $p$Ar collisions at $\sqrt{s_{NN}} = 110$ GeV



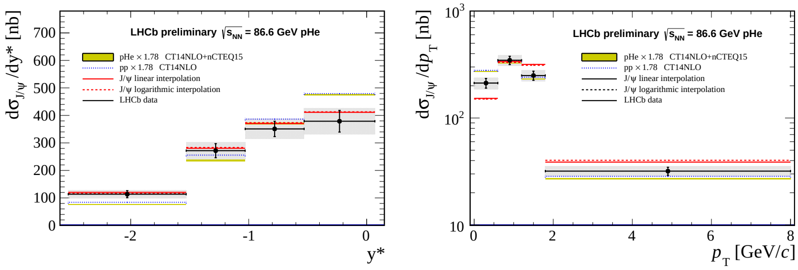

LHCb-PAPER-2018-023, in preparation.

- probing Bjorken-$x$: 0.02-0.16

  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y*}$

- HELAC-onia model EPJC 77 (2017) designed for collider data reasonable for rapidity, not working very well for $p_T$

# $J/\psi$ production in $p$He collisions at $\sqrt{s_{NN}} = 87$ GeV

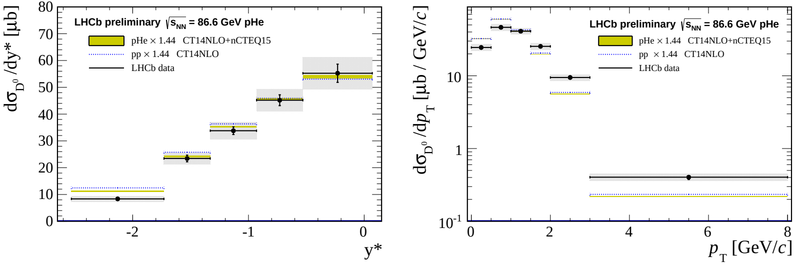



LHCb-PAPER-2018-023, in preparation.

- probing Bjorken-$x$: 0.03-0.37

  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y*}$
- in agreement for rapidity, tension for $p_T$ with phenomenological parametrisation JHEP 1303 (2013) 122
- HELAC-onia model designed for collider data reasonable for rapidity, not working well for $p_T$ and requiring scale factor of 1.78 EPJC 77 (2017)

# $D^0$ production in $p$He collisions at $\sqrt{s_{NN}} = 87$ GeV

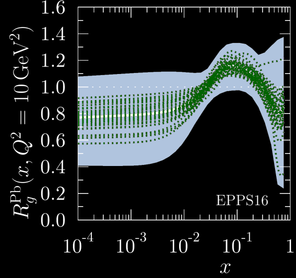



LHCb-PAPER-2018-023, in preparation.

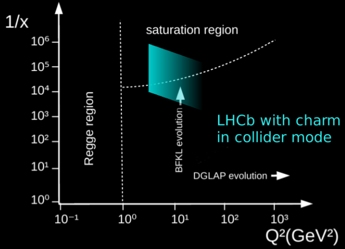
- probing Bjorken-$x$: 0.03-0.37

  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y*}$
- HELAC-onia model designed and tuned for collider reasonable for rapidity, not working well for $p_T$ and requiring a scale factor of 1.44 EPJC 77 (2017)
- no indication of visible valence-like intrinsic charm in rapidity distribution
- starting point for more detailed $p$-ion and future ion-ion collisions: open charm & charmonium down to 0 $p_{\mathrm{T}}$ at $\sqrt{s_{NN}} = 69$ GeV on Neon targets

# $p$–nucleus collider: control & limits of collinear factorisation




Eur.Phys.J. C77 (2017) no.3, 163

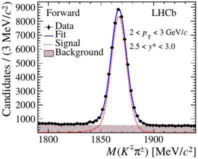


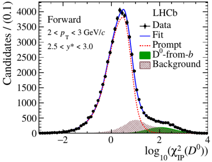

modified from "QCD and collider physics", Ellis, Stirling, Webber

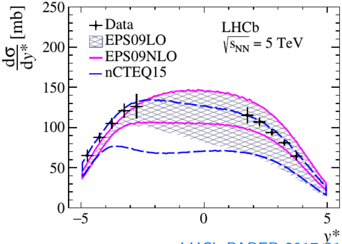
- **no HERA equivalent for lepton-nuclei**:
  partons largely **unconstrained** for LHC heavy-ions
- **saturation** scale $Q_s^2 \propto A_{nucleus}^{1/3}$ $\rightarrow$ linear parton evolution break-down?
  Color glass condensate Ann.Rev.Nucl.Part.Sci.60:463-489,2010?
- Other effects?

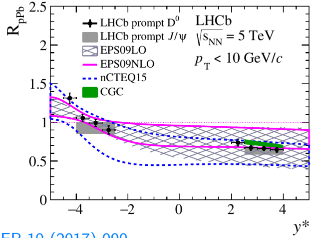
  as coherent energy loss by enhanced small-angle gluon radiation JHEP 1303 (2013) 122
- LHCb: forward acceptance + heavy-flavour
  $\rightarrow$ low, but perturbatively amenable $Q^2$ to reach low-$x$

# $D^0$ production in $p$Pb collisions at 5.02 TeV: precision data



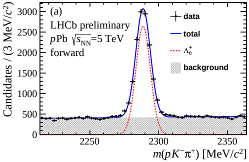



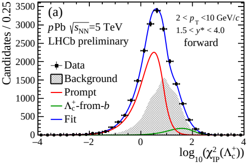

LHCb-PAPER-2017-015, JHEP 10 (2017) 090.

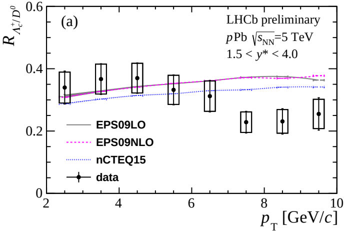
- strong suppression at forward rapidity, modification factor at backward rapidity close to 1, increasing in most backward bins
- nuclear PDFs EPJC 77 (2017) & color glass condensate calculation PRD91 (2015) no.11, 114005 accounting for observations

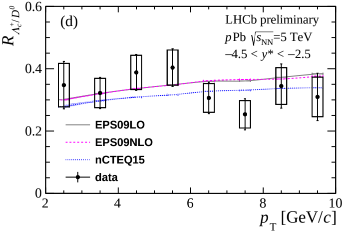
  coherent energy-loss JHEP 1303 (2013) 122 qualitatively similar expectation
- assuming no other effect:
  constraining nPDFs in unexplored area at low-$x$, see PRL 121, 052004 (2018)

# $\Lambda_c$ production in $p$Pb collisions at 5.02 TeV: test of charm fragmentation



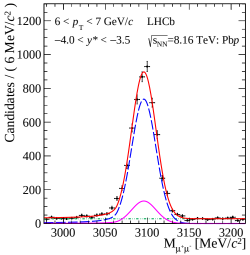



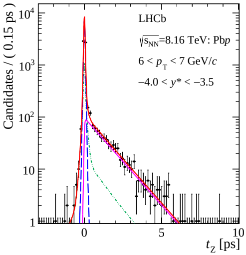



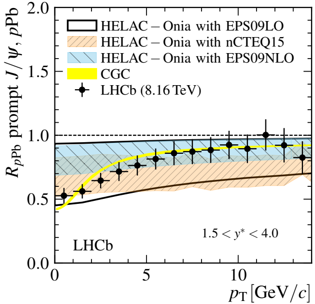

LHCb-PAPER-2018-021, in preparation.

- input for hadronisation phenomenology: crucial comparison with other collision systems
- hadronisation pattern of $c\bar{c}$ similar to model tuned to $pp$

# Prompt $J/\psi$ production in $p$Pb collisions at 8.16 TeV: precision nuclear modification



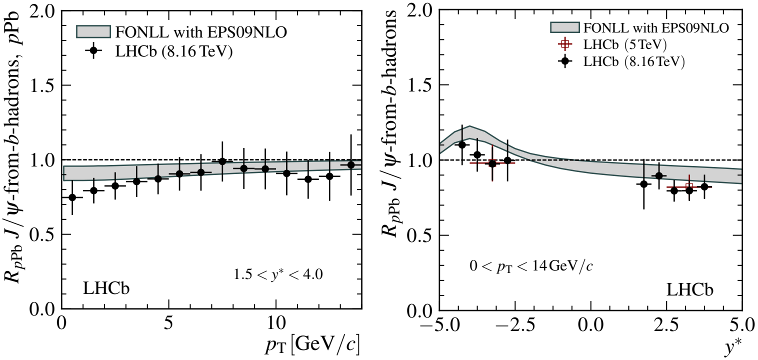




LHCb-PAPER-2017-014,PLB 774 (2017) 159.

- strong suppression at forward rapidity: increasing from 0.5 at lowest $p_T$ reaching 1 at highest $p_T$
- nuclear PDFs EPJC77 (2017) 1 & Color Glass Condensate calculations PRD91 (2015) no.11, 114005 accounting for observations

  coherent energy-loss JHEP 1303 (2013) 122 accounting for rapidity dependence
- assuming no other effect:
  constraining nPDFs in unexplored area at low-$x$, see PRL 121, 052004 (2018)

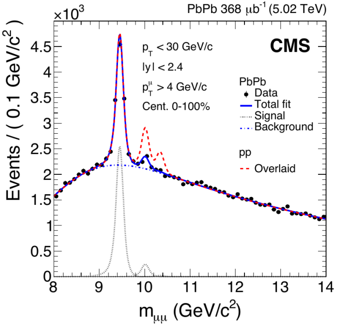
# Non-prompt $J/\psi$ production in $p$Pb collisions at 8.16 TeV: precision data on beauty



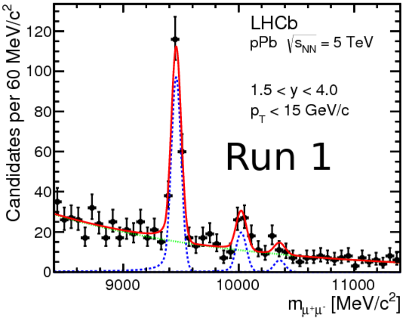

LHCb-PAPER-2017-014, PLB 774 (2017) 159.

- suppression at forward rapidity, modification factor at backward rapidity close to 1
- first precise $b$-production measurement in $p$Pb down to 0 $p_{\mathrm{T}}$
- crucial input for PbPb phenomenology
- assuming no other effect:
  constraining nPDFs in unexplored area at low-$x$, see PRL 121, 052004 (2018)

# $\Upsilon$(nS) in heavy-ions: probe of deconfinement



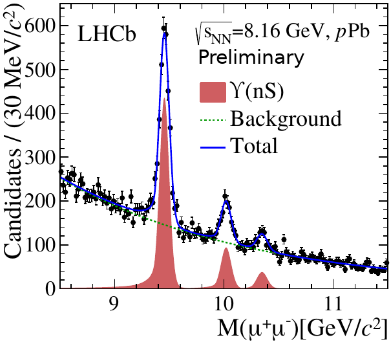

PRL 120 (2018) 142301




LHCb-PAPER-2014-015, JHEP 1407 (2014) 094

- quarkonium: QCD hydrogen atom $\rightarrow$ probe deconfinement in PbPb
- $\Upsilon$(nS) suppression patterns in PbPb by CMS and ALICE
- observed additional suppression of $\psi$(2S) and $\Upsilon$(2S,3S) at low-$p_T$ also in $p$Pb/Pb$p$ by LHC collaborations in Run 1
- LHCb Run 1 $\Upsilon$(nS) in $p$Pb/Pb$p$ statistically limited

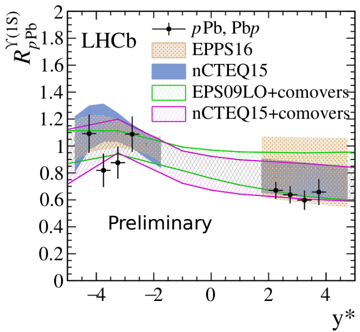
# $\Upsilon$(nS) production in *p*Pb and Pb*p* collisions with LHCb

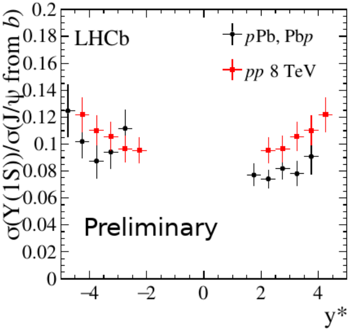



LHCb-PAPER-2018-035, in preparation.

- LHCb: factor 20 more luminosity in 2016 than in Run 1 to scrutinize the situation
  $\rightarrow$ fully profitting thanks to resolution and excellent $\mu$-PID

# $\Upsilon(1S)$ in $p$Pb and Pb$p$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV




LHCb-PAPER-2018-035, in preparation.

- $\Upsilon(1S)$: suppressed forward, compatible with unity backward → within nPDF uncertainties
- $p_T$-integrated $\Upsilon(1S)/J/\psi$-from-$b$ similar in $pp$ & in $p$Pb/Pb$p$:
  → naive approximate expectation in pure nuclear PDF & coherent energy-loss
  → 'additional' suppression limited for ground state
  → new observable:
  proxy for 'natural' normalisation by total $b\bar{b}$ with same final state

# $\Upsilon$(nS) suppression patterns in $p$Pb and Pb$p$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV

$$R(p\mathrm{Pb}/pp)[\Upsilon(2S)] = 0.86 \pm 0.15$$

$$R(p\mathrm{Pb}/pp)[\Upsilon(3S)] = 0.81 \pm 0.15$$

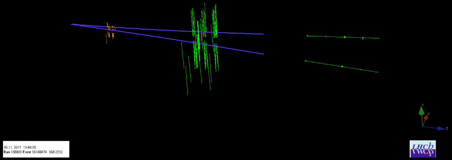
$$R(\mathrm{Pb}p/pp)[\Upsilon(2S)] = 0.90 \pm 0.21$$

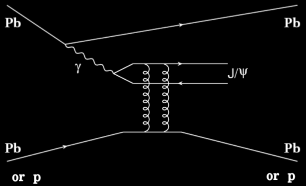
$$R(\mathrm{Pb}p/pp)[\Upsilon(3S)] = 0.44 \pm 0.15$$

LHCb preliminary LHCb-PAPER-2018-035, in preparation.

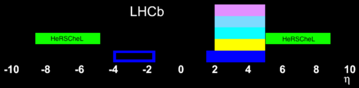
- additional suppression of excited states observed in inclusive collisions: significant for $\Upsilon(3S)$ in Pb$p$
  $\rightarrow$ factorisation with respect to final state broken
- in qualitative agreement with models invoking late time interactions in $p$Pb/Pb$p$
  PLB749 (2015) 98-103, NPA 943 (2015) 147-158, PRC 97, 014909 (2018)
- comprehensive understanding: ingredient for ion-ion collisions
  $\rightarrow$ upcoming prompt $\psi$(2S) LHCb measurement at 8.16 TeV will contribute

# Ultra-peripheral PbPb collisions: $\gamma$-probe of the nucleus



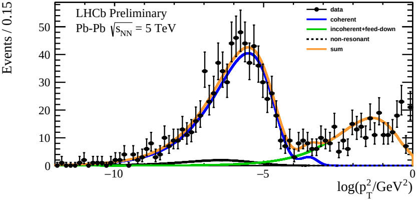


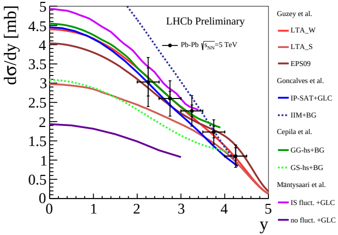

- exclusive vector meson production via $\gamma$-pomeron scattering
- sensitive to generalised gluon distributions for Bjorken-$x \in 10^{-2}$-$10^{-5}$
- for small $q\bar{q}$ at leading twist, leading $\ln(1/x)$, t$\rightarrow$0: $\sigma \propto$ (gluon PDF)$^2$
  PRD50 (1994) 3134-3144
- LHCb well suited for exclusive production studies with Pb-beams: resolution, PID & very forward detector HerSCheL




- LHCb experience: unique $\gamma$-p production studies in *pp* with quarkonium
  LHCb-PAPER-2018-011, arXiv:1806.04079; JHEP 1509 (2015) 084, LHCb-PAPER-2015-011; J. Phys. G41 (2014) 055002, LHCb-PAPER-2013-059; J. Phys. G40 (2013) 045001, LHCb-PAPER-2012-044

# Ultra-peripheral PbPb collisions at 5.02 TeV: first $J/\psi$ results

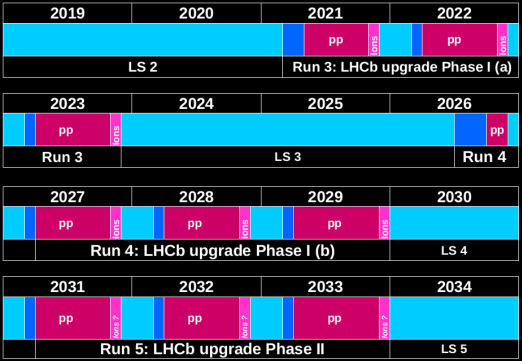



LHCb-CONF-2018-003.

- coherent $J/\psi$ production can be well separated from incoherent part
- covered rapidity range and precision constraining model space:
  Cepila et al. PRC 97 024901 (2018), Goncalves et al.: PRD 96, 094027 (2017) Guzey et al.: PRC 93, 055206 (2016), Mäntysaari, PLB 772 (2017) 832-838
- heavy-ions: Mäntysaari-Schenke requires fluctuations to describe data as for $v_n$ coefficients from particle correlations in $p$Pb collisions
- final publication: include HerSchel information
- 2018 data waiting with 10$\times$ larger luminosity and exploiting other final states in exclusive $\gamma$-induced reactions

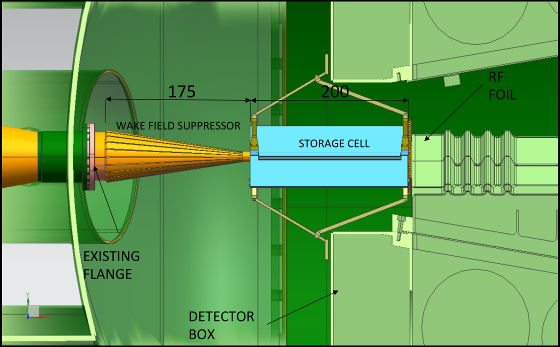
# Outlook collider




- heavy-ion Run 2 data started to be exploited:
  → largest heavy-flavour statistics in *p*Pb, forward acceptance & PID
- Phase I: $\approx 5 \times L_{inst}$(Run II) in *pp* LHCB-TDR-12 – 17
  - extend ion-ion capabilities
  - increase *p*A luminosity for low-*x* sector
- Phase II in design phase: $\approx 50 \times L_{inst}$(Run II) in *pp*
  → dream detector for heavy-ion physics

Physics case for an LHCb Upgrade II; CERN-LHCC-2018-026; LHCB-TDR-019

# Outlook fixed target




- pNe data sample from 2017: $\approx 10 \times p\mathrm{He}/p\mathrm{Ar}$
- large PbNe sample in 2018
- Run 3: plan for storage cell upstream, allow for non-noble gas targets, in particular $H^2$ and $\mathrm{D}^2$ as references
- 10-100 $\times$ larger instant. luminosity per unit length
- upgrades with crystal target for $c$-quark MDM, EDM
  polarised target further upstream & wire targets under discussion

# Conclusions:
# LHCb as versatile lab for heavy-ion & fixed-target collisions

- **fixed-target $p$He**:
  reference for direct cosmic ray $\bar{p}$ measurements

  - uncertainties mostly $< 10$ %: improve baseline for darkmatter searches

- **fixed-target $p$A**:
  high-$x$ tests: intrinsic charm & gluon pdfs at low scales

  - $y$ & $p_T$-distributions with $D^0$ & $J/\psi$ at backward $y$ with A=4/40:
  $y$-dependence reproduced by models

- **$p$Pb and PbPb collider**:
  tests of low-$x$ with perturbative probes in gluon and $\gamma$-induced reactions

  - nuclear suppressions in $p$Pb: up to 50% at low-$p_T$ in $p$Pb forward with charm and 20-30% for beauty
  - $d\sigma/dy$ of coherent $J/\psi$-production in PbPb collision constraining models

  test heavy-flavour bound state hadronisation & fragmentation down to low-$p_T$ with $\Lambda_C$ and $\Upsilon$(nS)

# Conclusions:
# LHCb as versatile lab for heavy-ion & fixed-target collisions

A precision experiment at low/moderate $Q^2$:

Unique acceptance at a hadron collider
- the world of colour charges & hadrons

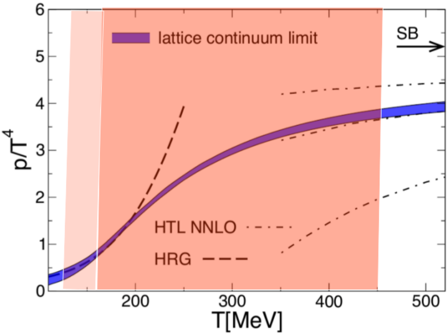
A chance:

- to measure soft QCD
- to probe the partonic content of nucleons and nuclei
- to investigate QCD many body systems

*Thanks a lot for two exciting years!*

# Back-up

# Heavy-ion collisions at the LHC as a probe of QCD matter




T-range probed at the LHC according to hydrodynamic models

PLB 370 (2014), T-range from PRC 89, 044910 (2014)

$p/T^4$: pressure over temperature$^4$

HRG: Hadron Resonance Gas

HTL: Hard thermal loop

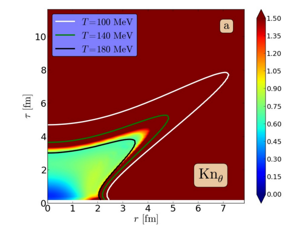
SB: Stefan-Boltzmann limit of

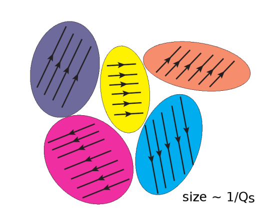
non-interacting quarks and gluons

The QCD many-body system in the lab: nucleus-nucleus collisions

- measure equilibrium properties:
  deconfinement, chiral restoration, thermodynamic&transport properties
- quantify QCD properties:
  QCD radiation, hadronisation, phase transition characteristics
- understand non-equilibrium dynamics and relation to equilibrium

# $p$-nucleus and $pp$ as a test of the heavy-ion paradigm




Left: arXiv:1404.7327 $Kn = L_{micro}/L_{macro}$. Right: arXiv:1611.00329

- correlations & bulk production@low-$p_{\mathrm{T}}$ & large multiplicity: **'same' patterns as in PbPb** where assumption of local thermalisation
- **hydro** in large multiplicity $p$Pb: set-up as in PbPb **describing data** despite **precondition doubts** PLB772 (2017) 681-686
- role of kinetic theory: to be quantified arXiv:1805.04081
- debate on saturation explanations of observed anisotropies arXiv:1808.01276 arXiv:1805.09342
- alternative: string interactions PLB779 (2018) 58-63
- LHCb: acceptance + heavy-flavour as hard scale: ideal testing ground